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Dynamics of vegetation autumn phenology and its response to multiple environmental factors from 1982 to 2012 on Qinghai-Tibetan Plateau in China

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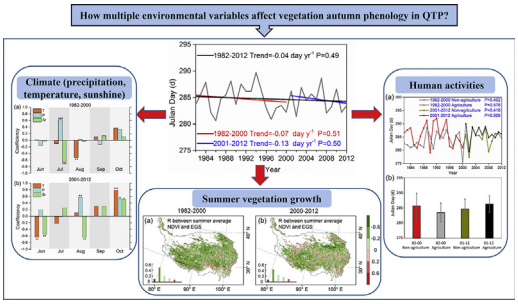
HIGHLIGHTS

- Dynamics of autumn phenology over the Qinghai-Tibetan Plateau were analyzed.
- Impacts of climate change on autumn vegetation phenology were evaluated.
- Vegetation growth in summer tends to induce an earlier vegetation dormancy.
- Moderate grazing will delay vegetation brown in autumn, while overgrazing will lead to an advancement of grass senescence.

GRAPHICAL ABSTRACT



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ABSTRACT

Autumn phenological shifts induced by environmental change have resulted in substantial impacts on ecosystem processes. However, autumn phenology and its multiple related controlling factors have not been well studied. In this study, the spatiotemporal patterns of the end date of the vegetation growing season (EGS) and their multiple controls (climate change, summer vegetation growth and human activities) over the Qinghai-Tibetan Plateau (QTP) were investigated using the satellite-derived normalized difference vegetation index (NDVI) based on GIMMS3g datasets during 1982–2012. The results showed that there was no significant temporal trend in the EGS during the period of 1982–2012. Spatially, there was a notable advancing trend in the southwest region and a delayed trend in the other regions of the QTP during 1982–2000, and this spatial trend was reversed during 2001–2012. We found average temperature, precipitation and sunshine duration of autumn exerted positive effects on EGS on the QTP, while average temperature and sunshine duration of summer exerted negative effects. Our results indicated that vegetation growth in summer tends to induce an earlier EGS in alpine vegetation, whereas summer vegetation degradation could delay the EGS on the QTP. In contrast, moderate grazing delays vegetation browning in autumn, while overgrazing leads to advancement of grass senescence. This study improves our understanding of how multiple environmental variables jointly affect autumn phenology and highlights the importance of biotic controls for autumn phenology on the QTP.

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1. Introduction

Land surface vegetation is a fundamental determinant that strongly impacts the carbon uptake, energy exchange, and hydrological cycles of ecosystem processes (Zeng, 1999; Cornelissen et al., 2007; Richardson et al., 2013). Vegetation phenology, which determines the timing and duration of active photosynthesis in the canopy, plays an important role in the annual carbon budget in terrestrial ecosystems (Richardson et al., 2010; Barichivich et al., 2012; Keenan et al., 2014). In addition, a change in vegetation phenology can affect a variety of ecosystem properties and exert feedback on the regional climate by altering the land–atmosphere energy exchange (Pearson et al., 2013). For example, the timing of the spring green-up and the autumn dormancy of vegetation substantially affect vegetation growth (Myneni et al., 1997), vegetation competition (Fridley, 2012) and surface albedo, which could further influence local temperature (Richardson et al., 2013). Therefore, the spatial and temporal patterns of vegetation phenology and its related environmental factors have received increasing attention in global change studies during the past several decades (Field, 2001; Guo et al., 2013; Xie et al., 2015; Fu et al., 2015; Crabbe et al., 2016).

Changes in spring phenology and their relationship with climate change have been extensively studied in the past few decades (Zhang et al., 2013; Clark et al., 2014; Keenan, 2015). In particular, advancement of spring green-up in response to a warming climate has been found in many studies based on ground observations (Parmesan and Yohe, 2003; Menzel et al., 2006) and satellite data (Piao et al., 2006a; White et al., 2009). Compared with spring phenology, knowledge of the variations of autumn phenology and its controlling factors remains limited. However, changes in autumn phenology play a critical role in determining growing season length and controlling carbon and nitrogen cycling and biotic interactions (Fridley, 2012; Pépino et al., 2013). Furthermore, recent studies showed that autumn phenology may contribute more than spring phenology to the extension of growing season length for temperate vegetation, implying that autumn and spring phenology play equally important roles in regulating the carbon balance (Doi and Takahashi, 2008; Jeong et al., 2011; Zhu et al., 2012).

Recent studies revealed a less consistent end of vegetation grow season in autumn. For example, using a meta-analysis of ground-based phenological observations throughout China, Ge et al. (2015) found that vegetation senescence in forests was delayed by 1.98 day decade^{-1} from 1960 to 2011. Based on long-term remote-sensing data, Liu et al. (2016) revealed that the dormancy was delayed by an average rate at 1.2 $\pm$ 0.1 days decade^{-1} from 1982 to 2011 in the temperate region of China. However, Jeong et al. (2011) reported an advanced autumn vegetation senescence in temperate North America using satellite data between 1982 and 2011. The lack of consistent relationship between EGS with temperature implies that the phenological processes of vegetation in autumn may be controlled by a suit of environmental factors, suggesting a compelling need to better understand the potential environmental triggers involved and the ways they influence changes in autumn phenology of vegetation.

The Qinghai-Tibetan Plateau (QTP) plays an important role in regulating climate change and water resources both in East Asia and globally (Qiu, 2008; Yang et al., 2011). The complex terrain and unique climate features of the QTP and increasing anthropogenic activities in the region jointly control the dynamic distribution of vegetation and result in obvious seasonal and spatial vegetation heterogeneity (Chen et al., 2013; Chen et al., 2014). Previous studies have indicated that higher temperature and more precipitation during the growing season tends to delay EGS for the alpine steppe and meadow on the QTP (Su et al., 2013). Photoperiod has also been suggested an important factor that controls vegetation autumn phenology (Bauerle et al., 2012; Gill et al., 2015), although its impacts on vegetation dormancy have not been assessed on the QTP. The effects of these factors on vegetation phenology were ecosystem dependent (Liu et al., 2016), the EGS of forest biomes was positively associated with temperature and photoperiod. For the grasslands, both temperature and precipitation modulated vegetation phenology, precipitation may be more closely linked to EGS in arid or semiarid areas, whereas temperature regulates the timing of EGS in cold regions.

In addition to the abiotic factors, biological factors, including competition, resource limitation, and genetics, could also regulate vegetation phenology, particularly during the period of a stable environment (Wolkovich et al., 2014). Furthermore, human activities such as agriculture, afforestation, grazing and tourism (Gilbert et al., 2006; Rauste et al., 2007), have been shown to affect autumn vegetation phenology. On the QTP, in particular, vegetation phenology could be affected by changes in species composition of the vegetation community due to overgrazing (Klein et al., 2004; Wu et al., 2008; Harris, 2010). In addition, numerous studies have indicated that change in vegetation activity is suggested to alter the local climate by changing surface albedo (Bounoua et al., 1999; Davin et al., 2007; Pearson et al., 2013). For example, vegetation growth could produce a positive feedback to climate warming through reduced albedo, which increases the amount of solar radiation absorbed by the surface, thus result in vegetation phenology change (Morisette et al., 2009). While vegetation degradation cloud produce a climate cooling effect by increase the albedo, which could affect vegetation phenology (Chen et al., 2011; Bisigato et al., 2013). However, some recent studies have attempted to explore variation in the EGS, which mainly focused on temperature and altitude on the QTP (Dong et al., 2012; Che et al., 2014) while neglecting the role of biotic factors, such as human activities and vegetation growth or degradation. Therefore, exploring the response of autumn phenology to climate change, vegetation growth or degradation and human activities is crucial for improving our understanding of how multiple factors interact to jointly affect the autumn phenology of alpine vegetation on the QTP.

Ground-based observations provide detailed phenological information for individual species with high accuracy; however, such information is often limited by spatial and temporal scales, and thus prevents it from being broadly utilized to examine vegetation responses to changing climate at larger scales (Zhu et al., 2012; Cong et al., 2013). Comparing with conventional techniques, satellite remote sensing offers an opportunity to capture vegetation information across a variety of spatial and temporal scales (White et al., 1997; Pinzon et al., 2005). Specifically, the Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) data set, which represents the longest NDVI time series to date, has been widely used in large-scale phenological studies (Tucker et al., 2005; Piao et al., 2006a; Jeong et al., 2011; Xu et al., 2016). In this study, we investigated the satellite-derived autumn phenology of vegetation and its relationship with climate change, summer vegetation growth or degradation and human activities on the QTP from 1982 to 2012. The GIMMS3g NDVI datasets were used to determine the end date of the vegetation growing season for the QTP. The EGS of each year in the QTP was retrieved from the datasets. The main objectives of this study were to (1) investigate the spatial and temporal patterns of the EGS on the QTP during the period of 1982–2012; (2) evaluate the effects of temperature, precipitation, and sunshine duration on the variation in the EGS across the QTP region; and (3) explore the responses of the EGS to summer vegetation growth or degradation and anthropogenic activities and discuss the underlying mechanism.

2. Materials and methods

2.1. Datasets

The NDVI has been shown to be a good indicator of the condition of surface vegetation, which is related to the photosynthetically active radiation absorbed by canopies (Huete et al., 2002). Global Inventory Modeling and Mapping Studies (GIMMS 3g) dataset was used to retrieve the EGS in our study. The GIMMS3g NDVI dataset was derived

from a National Oceanic and Atmospheric Administration (NOAA) satellite series and covered the period from 1982 to 2012, with a spatial resolution of 10 × 10 km and a temporal resolution of 15 days. This dataset has been corrected to minimize various errors and noises resulted from calibration, orbital drift, viewing geometry, stratospheric volcanic aerosols, and other factors unrelated to vegetation dynamics (Vermote et al., 1997; Sobrino et al., 2008; Pinzon and Tucker, 2014), and it is widely used for identifying long-term trends in vegetation activities (Tucker et al., 2005; Zhang et al., 2015).

Ecological regionalization data were obtained from the scheme of ecoregions in China (Fu et al., 2001). The ecological regionalization scheme considers factors such as human activities, natural vegetation and ecological functions. The study area was divided into four ecoregions: a southern Asia monsoon humid ecoregion (I), semi-humid broad-leaved evergreen forest ecoregion (II), needle-leaved forest and alpine steppe and meadow ecoregion (III), and alpine desert and semi-desert region (IV). The specific ecoregions and sub-regions of the QTP are shown in Fig. 1.

Daily temperature, precipitation, and sunshine duration data from 1982 to 2012 recorded at meteorological stations across the QTP were provided by the China Meteorological Data Sharing System (http://cdc.nmic.cn/home.do). Only 71 meteorological stations exhibited complete records and were used to calculate the monthly mean air temperature, monthly total precipitation and monthly sunshine duration (Fig. 1).

2.2. Retrieval of the EGS from satellite data

Snow cover often reduces the non-growing season NDVI, which results in errors in phenology extraction (Shen et al., 2014). In this study, we applied daily air temperature to help identify pixels that are probably covered by snow (below 0 °C for a sequence of 5 days) and replaced them with the nearest uncontaminated NDVI. This method has been validated in previous studies (Zhang et al., 2006; Liu et al., 2016). Subsequently, the Savitzky-Golay filter was used to distinguish abnormally high or low points resulting from residual noise before retrieving the EGS from NDVI annual time series (Chen et al., 2004; Zhang et al., 2015). These abnormal values were replaced by corresponding data from the fitted smooth curve of the NDVI time series.

In this study, we applied the dynamic threshold method to determine the EGS from time-series remote-sensing data. Dynamic thresholds were defined as NDVI ratios between the minimum and maximum values of annual NDVI cycling, which have been widely used to determine various phenological metrics (White et al., 1997, 2009; Yu et al., 2010; Shen et al., 2014). The NDVI ratio is described using Eq. (1):

$$NDVI_{ratio} = (NDVI_t - NDVI_{min})/(NDVI_{max} - NDVI_{min}) \quad (1)$$

where $NDVI_t$ is the NDVI value at a given time t and $NDVI_{max}$ and $NDVI_{min}$ are the maximum and minimum NDVI values, respectively, in

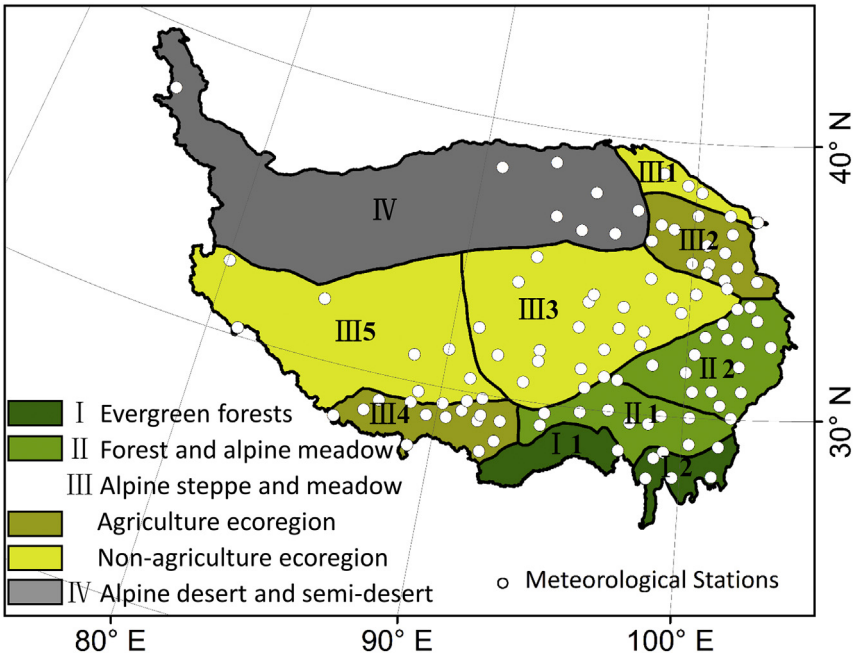

Fig. 1. Spatial distribution of meteorological stations and ecological regionalization in the Qinghai-Tibetan Plateau.

I Southern Asia monsoon humid and semi-humid broad-leaved evergreen forests

I1 mountainous tropical rainforest and seasonal rainforest ecoregion in the east of the Himalayas

I2 broad-leaved evergreen forests and dark coniferous forest in the Hengduan Mountains

II Forest and alpine meadow ecoregion

II1 broad-leaved evergreen forests and dark coniferous forests in the southeast of the Tibetan Plataea

II2 dark coniferous forest and alpine meadow ecoregion in the east of the Tibetan Plataea

III Alpine steppe and meadow ecoregion

III1 needle-leaved forest and alpine meadow ecoregion in the Qilian Mountains

III2 agriculture and pasturage ecoregion in eastern Qinghai

III3 alpine meadow ecoregion in the Changjiang-Yellow River region

III4 agriculture and pasturage ecoregion in South Tibet

III5 alpine steppe ecoregion in the Qiangtang Plateau

IV Alpine desert and semi-desert region

the annual NDVI time series. Specifically, the EGS was defined as the first day of the year in the descending period when the NDVI ratio decreased below 0.6 in this study. The thresholds of 0.6 were originally determined by Yu et al. (2010) based on ground observation data from the QTP. To reduce the influence of noise and bare soil or sparse vegetation on the NDVI time series, pixels showing a mean annual NDVI (from 1982 to 2012) lower than 0.1 were excluded from our study (Piao et al., 2006a; Jeong et al., 2011). Because a valid EGS (e.g., EGS less than zero or >365 days) may fail to be extracted for some pixels, only pixels with >50% of the valid EGS values were used for trend analysis. The entire phenology retrieval process was implemented in TIMESAT software (Version 3.1, http://www.nateko.lu.se/timesat/timesat.asp).

2.3. Statistics and analysis

We first calculated the EGS for each year and each pixel using the GIMMS3g NDVI datasets for the QTP for 1982–2012. Then, the ensemble mean annual value of the EGS for the entire QTP region was obtained from the dataset. We conducted the analysis of the temporal trend of the EGS using simple linear regression and determined its significance for each pixel. Because the national Grazing Withdrawal Program (GWP) policy and many other large-scale ecological projects were implemented after 2001 across the grasslands of north China, we selected 2001 as the breakpoint to analyze the effects of different environmental factors on changes in the autumn phenology of vegetation. Hence, the study period of these 31 years was divided into two subperiods: 1982–2000 and 2001–2012. The analysis of the EGS trend and the relationship between climate factors, summer vegetation growth or degradation and human activities was conducted separately for these two periods.

To evaluate the response of phenology to climatic factors from June to October, the monthly average temperature, monthly total precipitation and sunshine duration at each metrological station were calculated for each year, and the corresponding EGS values were derived based on the coordinates of the stations. Then, the mean EGS and monthly climate factors for all stations were calculated for each year. Finally, regression analysis between the annual EGS and corresponding monthly climate factors was applied. The impacts of summer (June to August) or autumn (September and October) climate factors on the EGS were assessed in a similar way. September and October were chosen to represent autumn because the growing season had ended by the end of October in 90% of the study region, according to the evaluated dataset.

Vegetation growth or degradation could produce an important feedback to local climate by change in albedo, which affected the amount of solar radiation absorbed by the surface, thus result in vegetation phenology change (Morisette et al., 2009). Therefore, we used the average summer (June, July, and August) NDVI as a surrogate of vegetation summer growth (Shen et al., 2015) to investigate the effect of summer vegetation growth on EGS. The increasing (decreasing) trend in average summer NDVI stands for the vegetation growth (degradation) for each pixel of study region. We performed a spatial correlation analysis between the annual EGS and average summer NDVI to investigate the relationship between the EGS and summer vegetation growth or degradation. The sensitivity of the EGS to vegetation growth was defined as the coefficient in the simple linear regression between the EGS and summer average NDVI during 1982–2000 and 2001–2012.

Finally, we investigated whether human activities influence vegetation EGS on the QTP. To further explore the regional influence of human activities on autumn phenology on the QTP, we simplified anthropogenic factors into whether grazing was occurring in the region. Because steppe and meadow represent the main grazing areas on the QTP, which are greatly affected by human activities, we chose ecoregion III to investigate the effect of grazing on vegetation phenology. Ecoregions III1, III3, and III5 were regionalized to an agriculture ecoregion, and ecoregions III2 and III4 were regionalized to a non-agriculture ecoregion. Then, analysis of the change in the annual mean EGS in the two ecoregions during the two study periods was conducted.

3. Results

3.1. Spatial pattern of the EGS on the QTP

The average EGS over the past three decades on the QTP region exhibited an obvious spatial pattern (Fig. 2a). Generally, the EGS exhibited a southeastward trend in arrival, ranging from the end of September at the northwestward edge, to the middle of October at the southwestern edge, and late as the end of October in the southeastern portions of the QTP (Fig. 2a). The EGS on the QTP showed substantial interannual variation for the whole period (Fig. 2b). The EGS exhibited an advancing trend from 1982 to 2000, with an annual advance of 0.07 days. A slight advancing trend with a rate of 0.13 days yr^{-1} was observed for the period of 2001–2012. Nevertheless, the trends from 1982 to 2000 and 2001–2012 were not statistically significant ($P > 0.1$).

Next, we characterized the spatial patterns of the trend for the EGS during two periods, 1982–2000 and 2001–2012. The spatial distribution of the EGS trend exhibited obvious spatial heterogeneity over the QTP in these two periods. During the period from 1982 to 2000, 63.5% of the vegetation pixels showed an advancing trend in the EGS, with 9.8% significant at the $P < 0.1$ level. Great advances are generally concentrated in the central and western parts of the QTP, whereas pixels showing a delayed trend were observed in the eastern part of the QTP (Fig. 3a). However, the EGS trend changed or even reversed in some regions during 2001–2012. Compared with the proportion in 1982–2000, a large proportion of areas in the central and eastern parts of the QTP showed an advancing trend in the EGS, whereas the southwestern QTP showed an obvious delay in the EGS during 2001–2012 (Fig. 3b).

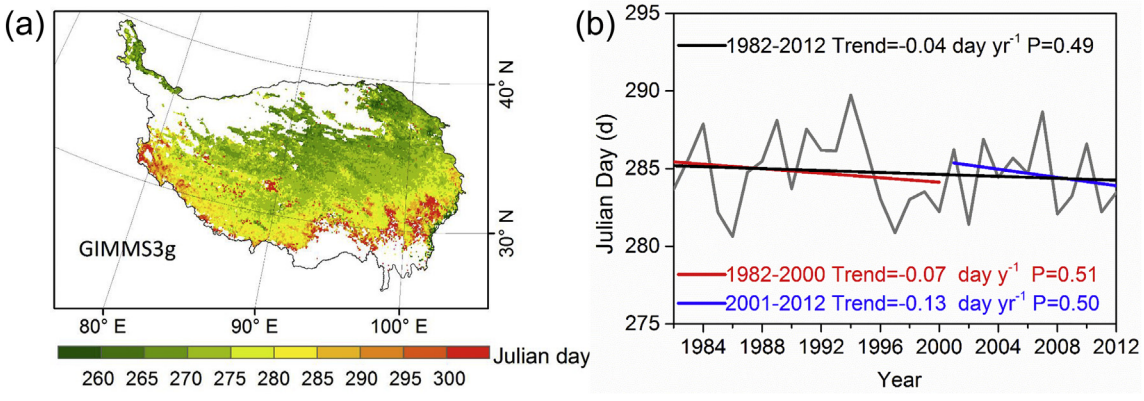

Fig. 2. Spatiotemporal pattern of the end date of the vegetation growing season (EGS) on the QTP during 1982–2012. (a) Spatial distribution of the EGS during 1982–2012 (multiyear mean for the GIMMS3g dataset). (b) Annual variations in the EGS during 1982–2012.

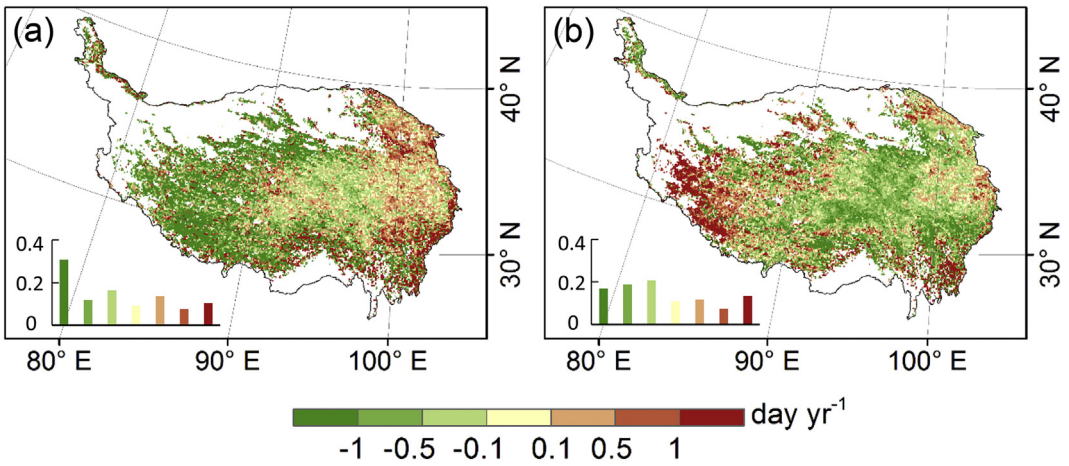

Fig. 3. Spatial patterns of trends at the end date of the vegetation growing season (EGS) for two periods. The inserted plot in each panel shows the percentage distribution of the pixels in each interval of the change trend. (a) 1982–2000; and (b):2001–2012. A negative value indicates an advance, and a positive value indicates a delay.

3.2. Responses of the EGS to climate factors

To investigate the influence of climate factors on the change of the EGS, the linear correlations between the EGS and monthly climate factors were analyzed. During the period of 1982–2012, significant negative relationship between temperature and EGS was observed in August ($P < 0.05$), while this relationship was significant positive in September and October at the $P < 0.05$ and $P < 0.01$ levels, respectively. Precipitation exhibited a positive influence on the EGS in most months, except in June, which exhibited a weak negative relationship. Unlike precipitation, it shows a negative relationship between the EGS and sunshine duration in June, July and August, whereas a positive relationship was observed in September and October (Fig. 4a). During 1982–2000, the correlation between the EGS and temperature was positive in September and October but negative in July and August. The correlation between the EGS and precipitation was significant positive in July ($P < 0.01$). In contrast to precipitation, the EGS exhibited a significant negative relationship with sunshine duration in July ($P < 0.01$) (Fig. 4b). During 2001–2012, temperature was significant negatively related to the EGS in June ($P < 0.05$), but this relationship was positive in October ($P < 0.05$). The correlations between the EGS and precipitation were significant positive in August and October ($P < 0.05$ and $P < 0.1$, respectively). Sunshine duration was significantly negatively related to the EGS in June and August ($P < 0.05$); however, this relationship was positive in July, September and October (Fig. 4c).

We also investigated the relationships between the EGS and climate factors in summer (June to August) and autumn (September to October). The results showed a negative relationship between the EGS and summer average temperature and sunshine duration, whereas a positive relationship between the EGS and summer average temperature and sunshine duration was observed in autumn. Unlike temperature and sunshine duration, precipitation exhibited a positive influence on the EGS in summer and autumn (Table 1). In general, the effects of climate factors on the EGS were found to be significant in summer and autumn during 2001–2012, except for the relationship between autumn sunshine duration and the EGS. In contrast, the relationships between climate factors and the EGS were relatively weak during 1982–2000.

3.3. Responses of the EGS to summer vegetation growth

We spatially compared the trend of summer vegetation growth with the annual change in the EGS. The relationship between the summer average NDVI and the EGS showed obvious spatial variation (Fig. 5). Negative correlations were observed on most parts of the plateau (82.6% of the total pixels) during the period 1982–2000, and this negative correlation was significant (26.4%) on part of the QTP at the $P < 0.10$ level (Fig. 5a). A statistically significant positive correlation between the summer NDVI and the EGS was observed in only approximately 1.7% of the pixels (at $P < 0.10$), which indicated a negative impact of the change in summer vegetation activities on the vegetation EGS. Similar to the period 1982–2000, widespread negative correlations between the summer average NDVI and EGS were observed over the QTP during 2001–2012 (Fig. 5b), with the correlations for 19.5% of the total pixels being significant at the $P < 0.10$ level. While 22.1% of the pixels with a positive correlation were scattered in the central and northern parts of the QTP, the correlation was statistically significant for only 1.8% of the pixels (at $P < 0.10$).

We further determined the sensitivity of the EGS to summer NDVI by regressing the EGS against the summer average NDVI for all pixels on the QTP. The majority of pixels showing a high sensitivity (>1 day per 0.01 summer NDVI units) of the EGS to summer NDVI were found in the western and center portions of the plateau, while the eastern portion exhibited relatively lower sensitivity (Fig. 5c). In contrast, the sensitivity of the EGS to the change in the summer NDVI for the period 2001–2012 shared the same sign as the period 1982–2000, while a slight positive impact of the summer NDVI on the EGS (<1 day per 0.01 summer NDVI units) was found in the eastern part of the plateau (Fig. 5d).

3.4. Responses of the EGS to human activities

To further investigate the possible causes of the trend of the EGS on the QTP, we quantified the influence of human activities on the vegetation EGS by analyzing the annual change in the EGS for agriculture ecoregion and non-agriculture ecoregion. The annual changes in the EGS for these two ecoregions showed larger differences during both 1982–2000 and 2001–2012 (Fig. 6). From 1982 to 2000, the EGS in agriculture ecoregion advanced at a rate of 0.20 day yr^{-1} ($P > 0.1$); however, this trend slowed during 2001–2012. In contrast, the EGS in non-agriculture ecoregion showed no significant temporal trend during 1982–2000 ($P = 0.402$) or 2001–2012 ($P = 0.416$) (Fig. 6a).

Interestingly, we found that the range of the EGS in agriculture ecoregion was relatively stable, while a larger annual change of the EGS was observed in non-agriculture ecoregion for the two study periods (Fig. 6a). Furthermore, our results showed that the EGS in agriculture ecoregion occurred earlier than that in non-agriculture ecoregion before 2000 (Fig. 6b). However, this gap was gradually reduced and

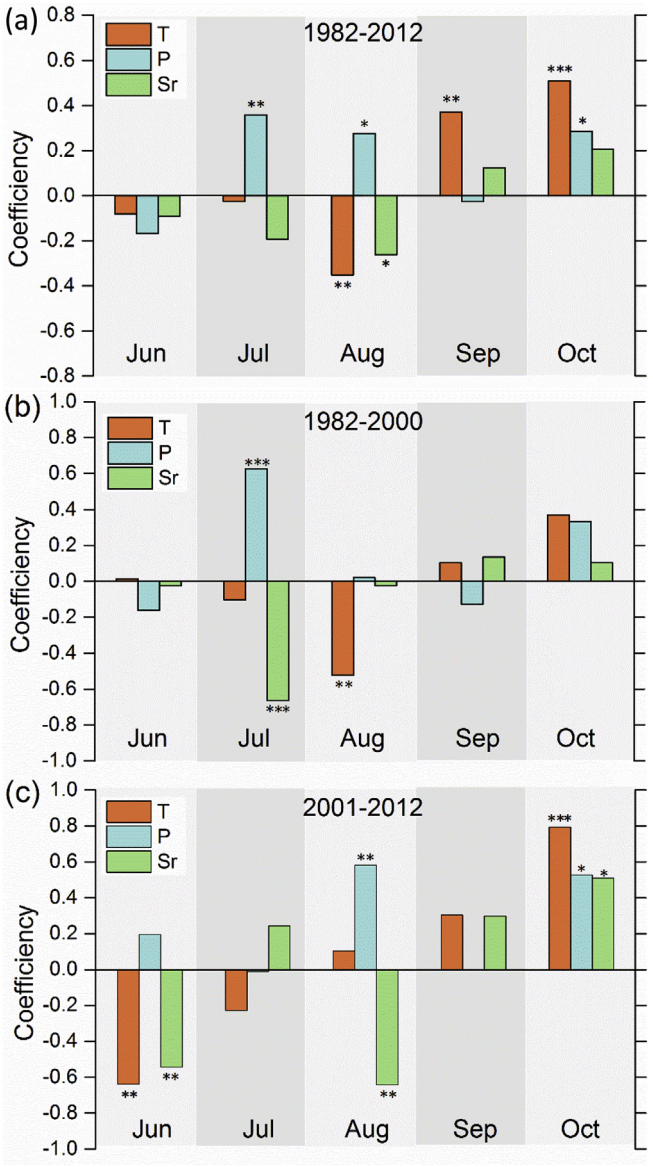

Fig. 4. Correlation coefficients between the annual changes in the end date of vegetation growing season (EGS) and monthly temperature (T), total precipitation (P), and sunshine duration (Sr) for the 71 valid meteorological stations across the QTP from 1982 to 2012. Significance: *** $P < 0.01$; ** $P < 0.05$; and * $P < 0.1$. Correlations with no asterisk are not significant ($P > 0.10$).

reversed for the period from 2001 to 2012, during which the EGS in agriculture ecoregion occurred later than in that in non-agriculture ecoregion (Fig. 6b).

Table 1
Correlation coefficients between the annual changes in the end date of the vegetation growing season (EGS) and the climate factors in summer and autumn during the periods from 1982 to 2000 and 2001–2012.

Period	1982–2000			2001–2012		
	T	P	Sr	T	P	Sr
6–8	−0.30	0.16	−0.39*	−0.44*	0.50**	−0.60**
9–10	0.29	0.26	0.19	0.68***	0.46**	0.28

Significance: *** $P < 0.01$; ** $P < 0.05$; and * $P < 0.1$. Correlations with no asterisk are not significant ($P > 0.10$). T: monthly temperature, P: total precipitation, and Sr: sunshine duration.

4. Discussion

4.1. Variation in autumn phenology across the QTP

Our results for the long-term remote-sensing NDVI time series showed no significant trend in the EGS over the QTP during 1982–2012. Several previous studies based on long-term remote-sensing data also found no significant temporal the EGS trend in alpine grassland on the QTP (Che et al., 2014; Yang et al., 2015; Liu et al., 2016). Our results regarding the annual change trend of the EGS over the same subperiod were in good agreement with the results obtained by Che et al. (2014), who analyzed the spatial and temporal variation in the EGS on the QTP using long-term series of LAI data from 1982 to 2011. A similar result was obtained by Yang et al. (2015), who reported a slight advancing trend (0.006 day yr^{-1}) in alpine grassland over temperate China based on GIMMS3g NDVI data from 1982 to 2010. Our results indicate that the insignificance of the EGS trend at a regional scale mainly results from the opposing trends between the southwestern QTP and the remaining areas. The EGS in the southwestern QTP exhibited a reversed change trend during the two periods, although the climate on the southwestern QTP was continually changing. The observed reversed change trend in the EGS indicates a complicated nonlinear response of the autumn phenology of vegetation to multiple factors (Yang et al., 2015). Interestingly, a previous study identified an analogous shifting pattern in spring phenology during the same period on the southwestern QTP (Shen et al., 2014), suggesting that autumn phenology dynamics are also affected by the timing of spring phenology (Keenan, 2015).

4.2. Effects of climate factors on the EGS

Several previous studies have showed that temperature plays a key role in regulating the autumn phenology of vegetation (Gill et al., 2015; Xie et al., 2015). A warmer preseason temperature could favor vegetation growth and thus lead to a delay in the EGS (Delpierre et al., 2009; Ge et al., 2015). However, our research revealed a complex relationship between temperature and the EGS. Although some differences existed between the two periods, we found that an increasing summer (6–8) temperature led to an advanced EGS across the regional scale of the QTP, whereas a warmer autumn temperature showed a positive influence on the EGS for the entire study period. The negative correlation between summer temperature and EGS could have occurred because higher temperatures in the summer may lead a decreased water content in the soil and plants, thus restraining vegetation growth and resulting in an advanced EGS in autumn (Che et al., 2014).

Additionally, our results showed positive effects of cumulative summer and autumn precipitation on the EGS in both periods, especially in the period of 2001–2012, in which the positive effect of precipitation was significant at the $P < 0.05$ level. These positive correlations between cumulative precipitation and the EGS suggested that increased preseason precipitation would promote vegetation growth in autumn. Studies have indicated that precipitation also plays an important role in determining vegetation phenology, especially in arid and semiarid regions, where soil water is limited (Liu et al., 2016). Moreover, multiple lines of evidence suggest that limited water increases the risk of chlorophyll degradation and plant mortality, thus advancing the timing of leaf senescence (Munné-Bosch and Alegre, 2004; Anderegg et al., 2013; Dreesen et al., 2013). Hence, increased precipitation during the preseason period could mitigate drought stress and delay vegetation dormancy in arid and semiarid regions.

Interestingly, we found that the EGS was negatively associated with summer sunshine duration but positively correlated with autumn sunshine duration in both study periods on the QTP. Because the maximum possible sunshine for one day is determined by the intensity of direct solar radiation (Kaiser, 2002). Our finding suggests that the insolation may also be involved in controlling the date of the EGS in alpine

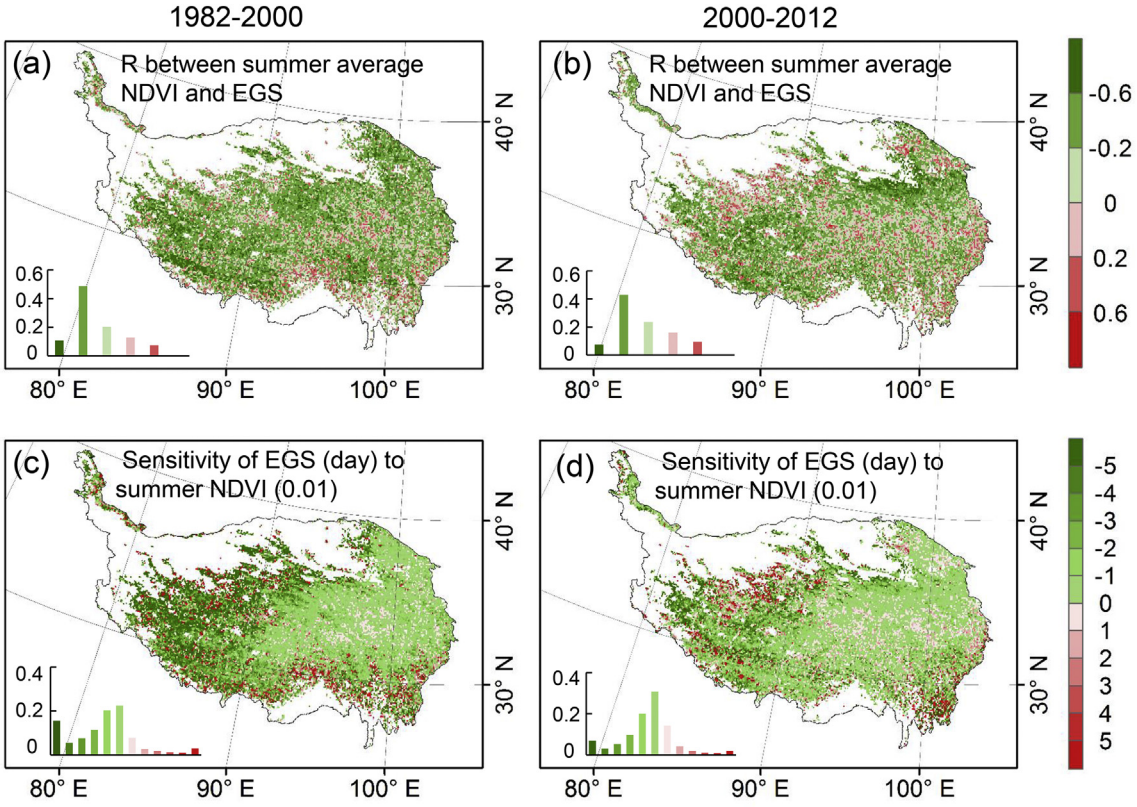

Fig. 5. Relationship between the end date of the vegetation growing season (EGS) and summer average NDVI. Top, spatial patterns of correlation coefficients between the EGS and summer average NDVI for the two periods, from (a) 1982–2000 and (b) 2001–2012. Bottom, spatial patterns of the sensitivities of the EGS to summer average NDVI for the two periods. The inset in each panel shows the percentage distribution of the pixels in each interval of the correlation coefficient or sensitivity indicated in the legend on the right.

vegetation. In general, higher insolation can enhance the photosynthetic capacity of vegetation (Bonan, 2002), postpones the accumulation of abscisic acid, and thereby slows the rate of leaf senescence (Thimann and Satler, 1979a, 1979b; Gepstein and Thimann, 1980). However, excessive radiation may increase surface evapotranspiration, which enhances the effect of drought on vegetation in the plateau and results in an earlier end date of the vegetation growing season (Hua et al., 2009). Moreover, most of the area of the QTP is semiarid, and thus, excessive radiation may result in water scarcity, which would further advance the senescence of vegetation (Che et al., 2014). Additionally, increased radiation in autumn would increase the temperature and stimulate photosynthesis, which would lengthen the growing season.

4.3. Effects of summer vegetation growth on the EGS

The vegetation on the QTP has experienced significant changes as a consequence of both climate change and human activities (Chen et al., 2013). For example, an obvious degradation trend of vegetation was observed on the southwestern QTP due to continuous drought during the period of 2001–2012 (Chen et al., 2014). Changes in vegetation activities will lead to changes in albedo, evapotranspiration and emissivity (Field et al., 2007; Pearson et al., 2013) and will exert feedback on climate, thus indirectly affecting vegetation phenology (Morisette et al., 2009). Our results showed widespread negative correlations between the EGS and summer vegetation activities in most parts of the plateau during the entire study period, suggesting that vegetation growth in summer will negatively influence the EGS, whereas vegetation degradation in summer will extend the growing season in autumn. We propose three hypotheses to explain the negative correlation between the EGS and summer NDVI on the QTP:

First, low rainfall (<500 mm yr^{-1}) (Piao et al., 2006b) and high potential evapotranspiration (>600 mm yr^{-1}) (Chen et al., 2006) result in a dry climate in most areas of the QTP, so the effects of vegetation growth or degradation on vegetation dormancy may be related to their influence on the water consumption. Increasing vegetation growth results in the consumption of more water (Jackson et al., 2005), thus resulting in a water shortage in autumn that leads to an earlier EGS on the QTP, whereas vegetation degradation would produce the opposite effect. Second, increasing vegetation activities can produce a warming effect through changes in surface albedo, which increases the amount of solar radiation absorbed by the surface and results in an increasing local temperature (Chapin et al., 2005; Pearson et al., 2013). The increasing local temperature further leads to water shortages in the plants and soil of the QTP. In contrast, vegetation degradation cools the local surface temperature in summer through increasing the surface albedo (Chen et al., 2011), thus mitigating the evaporation from plants and soil caused by increasing summer temperatures and radiation. Third, increased vegetation growth results in a requirement for more water transpiration (Shen et al., 2015), which will aggravate the water insufficiency in autumn and result in earlier autumn dormancy. In summary, vegetation activities may regulate the water supply to affect the autumn phenology of vegetation.

4.4. Effects of human activates on the EGS

Grazing exerts the most important anthropogenic impact on the ecosystem of the QTP (Chen et al., 2013; Harris, 2010); however, it is difficult to disentangle the effects of grazing and other environmental factors. Previous studies have suggested overgrazing leads to grassland degradation or even desertification (Dirnböck et al., 2003; Song et al., 2009; Eldridge et al., 2013). In particular, species composition of the plant communities on the QTP has been dramatically changed under

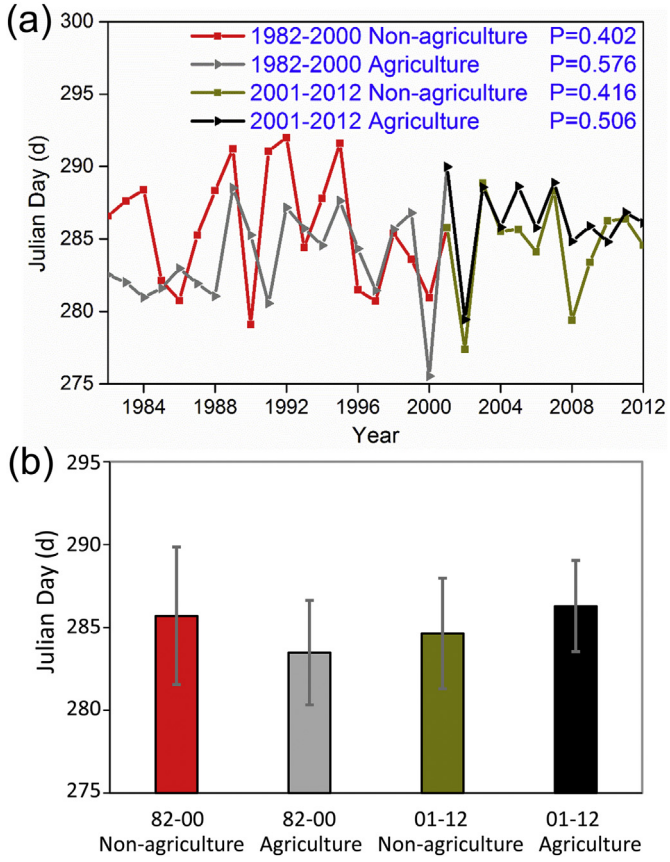

Fig. 6. Comparisons between the end date of the growing season for different distributed regions of agriculture and non-agriculture ecoregion on the QTP during 1982–2000 and 2001–2012. (a) Interannual variations in the end date of the vegetation growing season (EGS) for agriculture and non-agriculture ecoregion. (b) The average EGS for agriculture and non-agriculture ecoregion. Error bar indicates one standard deviation.

heavy grazing pressure, leading to plants in the *Cyperaceae* and *Poaceae* losing their dominance and being replaced by low-growing plants, such as weeds in *Asteraceae, Fabaceae*, and *Scrophulariaceae* (Harris, 2010; Klein et al., 2004; Wu et al., 2008). Thus, overgrazing reduced the leaf biomass and plant height, and limited the regrowth ability of vegetation on the QTP, resulting in the early onset of grass browning.

The number of livestock decreased sharply on the QTP after 2000 as the government's national conservation policies under the GWP were implemented (Mu et al., 2013). Moreover, many large-scale ecological projects, such as ecological compensation, restoration of land cover vegetation and fencing of degrading grassland, were implemented during 2001–2012 (Mu et al., 2013; Chen et al., 2014). These measures further reduced grazing pressure over the QTP, leading to a delay of vegetation browning under a proper grazing intensity. Two interpretations relating plant autumn phenology responses to moderate grazing may be relevant in interpreting our results. One is that moderate grazing can speed up the recycling of nutrients and the flow energy into the soil, in addition to promoting the irradiance of the ground surface and canopy layer (Louault et al., 1997; Schlesinger et al., 2006). Consequently accelerating grass regrowth and delaying the date of grass browning (Wang et al., 2015). An alternative reason is that alpine ecosystems may be particularly vulnerable to climate changes (Zhou et al., 2016). Several studies have shown that moderate grazing could improve the species diversity, richness and evenness of plant communities and thus tend to reinforce the stability and self-adjustive ability of vegetation ecosystem, which prevent alpine vegetation from climate change and other disturbances (Sparrow et al., 2003; Klein et al., 2004; Niu et al., 2009). Therefore, proper grazing intensity could mitigate the effects of climate change on vegetation (Klein et al., 2004), and prevent vegetation from entering dormancy early because of unfavorable environment. This explained why a relatively later EGS was observed in the agriculture ecoregion than in the non-agriculture ecoregion after 2000. Our results also showed a stable annual change in the EGS in the agriculture ecoregion during both periods, suggesting that the EGS in the agriculture ecoregion may be subject to less climatic influence than the non-agriculture ecoregion and that moderate grazing can mitigate the effects of climate change on vegetation.

5. Uncertainties and limitations

Although the trend of the satellite-retrieved EGS was consistent with the findings of previous studies, a certain degree of uncertainty was unavoidable in the estimation of the EGS in this study. It has been shown that several aspects of shortcomings in AVHRR sensor design and data processing which potentially introduce substantial noise into the GIMMS 3g NDVI dataset (Steven et al., 2003; Fensholt and Proud, 2012). For example, the post-launch degradation in sensor calibrations and drift in the satellite overpass times could produce a significant impact on time series of observed NDVI (Pinzon et al., 2005; Tucker et al., 2005). Furthermore, because of inaccurate atmospheric correction scheme for AVHRR sensors, the spectral configuration was aborted and scattered by atmospheric components such as water vapour (Tanré et al., 1992) and aerosols (Nagol et al., 2009), which would result in error in the observed NDVI trends. In particular, on the QTP, snow cover will have an impact on the quality by detected NDVI value, however, the AVHRR NDVI product does not include snow information. Therefore, multiple datasets are suggested to assess the changes in vegetation phenology in future research because of the differences in different sources of data. Here, we assessed the trend of vegetation phenology based on a single method, mainly because our dynamic threshold of 0.6 has been validated through field-based measurements on the QTP (Yu et al., 2010). In addition, the same trend was found for the annual phenological metrics using five different remote sensing-based methods despite large differences in the derived vegetation phenology (Cong et al., 2013; Shen et al., 2014), which suggests that even though some uncertainty might be associated with the derived EGS, the EGS trend may be applicable for the analysis of longer temporal scales (Zhu et al., 2012).

In this study, we simplified anthropogenic factors into whether the region was grazed or not; however, there are also anthropogenic activities in non-agriculture ecoregion. In fact, the effects of climate change and anthropogenic activities on vegetation phenology were not completely distinguishable in this study. This situation could result in some uncertainty in indirectly evaluating the regional influence of anthropogenic activities on vegetation phenology. Therefore, further work is needed to fully and precisely separate the effects of climate change and human activities on ecosystems in the sub-region. Moreover, it is very important to characterize and quantify the impact of anthropogenic activities on the autumn phenology of vegetation and integrate these data into vegetation phenology models. In addition, apart from climate factors and human activities, the autumn phenology of vegetation has also been shown to be regulated by many other environmental factors, such as freeze-thaw processes, extreme weather events, atmospheric CO_2 concentrations and their combined effects (Chen et al., 2011; Reyes-Fox et al., 2014; Yang et al., 2015). Obtaining a comprehensive understanding of the combined environmental controls on the autumn phenology of vegetation remains a great challenge for future research.

6. Conclusions

Based on satellite-derived time-series GIMMS3g NDVI datasets and the dynamic threshold method, we have identified notable advancing trends of the EGS in the southwestern QTP and extensive delayed trends in other areas during the period 1982–2000; however, this trend was

reversed during 2001–2012. Our results indicated that autumn temperature, precipitation, and sunshine duration play a positive role in delaying autumn phenology, whereas summer temperature and sunshine duration exert a negative influence on the EGS. In addition to climate factors, vegetation growth or degradation and human activities may also contribute to the autumn phenology of vegetation. Vegetation growth can lead to an advanced EGS through increasing the local temperature, while vegetation degradation will delay the EGS. Moderate grazing can promote vegetation regrowth and results in a delayed EGS; however, overgrazing leads to an earlier EGS. These observations indicate that multiple factors jointly regulate the change in autumn phenology over the QTP. Thus, more mechanical studies with well-designed experiments are certainly needed to better understand autumn phenology and its environmental controlling factors.

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